ESTCP
Cost and Performance Report

(MR-201420)

Data Collection using the MetalMapper in Dynamic Data Acquisition and Cued Modes

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The overall objective for both sites used in the project (Fort Ord and RSA) was to demonstrate and validate Advanced Classification (AC) techniques in challenging site conditions. At Fort Ord, the primary challenge was to detect and classify munitions in areas with high subsurface metallic clutter. The primary challenge at RSA was to collect high-quality advanced sensor data in highly wooded areas that could be used for classification. Each site also had additional unique objectives that were determined in concurrence with CB&I, the U.S. Army Corps of Engineers (USACE), and project stakeholders during the project planning phase.

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ACRONYMS AND ABBREVIATIONS

µs	microsecond(s)
AC	Advanced Classification
ADEM	Alabama Department of Environmental Management
bgs	below ground surface
BRAC	Base Realignment and Closure
BTG	Black Tusk Geophysics
BUD	Berkeley UXO Discriminator
CB&I	CB&I Federal Services LLC
cm	centimeter(s)
DGM	digital geophysical mapping
DTSC	Department of Toxic Substances Control
EM	electromagnetic
ESTCP	Environmental Security Technology Certification Program
FM	titanium tetrachloride
ft	foot/feet
GPS	global positioning system
GX	executable
HE	high explosive
Hz	hertz
IM-AE	Isobutyl Methacrylate Incendiary Mix
IMU	inertial measurement unit
in	inch(es)
ISO	industry standard object
IVS	instrument verification strip
kHz	kilohertz
m	meter(s)
MEC	munitions and explosives of concern
MM	MetalMapper
mm	millimeter
MPV	Man Portable Vector
MQO	measurement quality objective
ms	millisecond(s)
mV	millivolt(s)

mV/A	millivolt(s) per Ampere
NRL	U.S. Naval Research Laboratory
PVC	polyvinyl chloride
QA	quality assurance
QC	quality control
RMS	root mean square
ROD	Record of Decision
RSA	Redstone Arsenal
RTK	Real-Time Kinematic
RTS	Robotic Total Station
SFTP	secure file transfer protocol
TDEM	time-domain electromagnetic
TEMTADS	Time-domain Electromagnetic Multi-sensor Towed Array Detection System
TOI	target of interest
USACE	U.S. Army Corps of Engineers
UTM	Universal Transverse Mercator
UXO	unexploded ordnance
WP	white phosphorous

EXECUTIVE SUMMARY

CB&I Federal Services LLC (CB&I) geophysicists participated in the Environmental Security Technology Certification Program (ESTCP) Demonstration of Advanced Geophysics and Classification Technologies on Munitions Response Sites at the Former Fort Ord, California (Fort Ord), and Redstone Arsenal, Alabama (RSA) (project MR-201420).

At Fort Ord, CB&I collected approximately five acres of dynamic MetalMapper (MM) data, which included high, medium-high, medium, and low anomaly density areas. The resulting data was used to select targets for cued measurements. Cued measurements were then used to model each target source, which resulted in the creation of a prioritized dig list. All targets were investigated for evaluation of the classification effort.

At RSA, CBI collected approximately 8.21 acres of dynamic Time-domain Electromagnetic Multi-sensor Towed Array Detection System (TEMTADS) 2x2 data in various site conditions, including high-density anomaly areas, heavily wooded areas, and areas subject to site cultural noise. The resulting data were used to select targets for cued measurements. Cued measurements were then used to model each target source, which resulted in the creation of a prioritized dig. Of these cued measurements, 221 targets were selected for subsurface investigation. The methods and results from both studies are summarized in this report.

OBJECTIVES OF THE DEMONSTRATION

The ability to safely and efficiently locate, identify, and remove buried objects on practice and test ranges is critical to the U.S. Department of Defense's mission and its goals of safe operation, sustainability, and environmental stewardship. Although several robust, advanced sensor technologies have been developed for discriminating buried objects on ranges as targets of interest (TOIs), widespread acceptance of the technologies requires that they be demonstrated on live sites, where the impact of operating and data acquisition and analysis parameters can be fully evaluated. The potential benefit of the technology is to reduce the number of subsurface investigations that are required to remove hazardous munitions and explosives of concern (MEC) in areas where subsurface clearance is required.

The overall objective for both sites used in the project (Fort Ord and RSA) was to demonstrate and validate Advanced Classification (AC) techniques in challenging site conditions. At Fort Ord, the primary challenge was to detect and classify munitions in areas with high subsurface metallic clutter. The primary challenge at RSA was to collect high-quality advanced sensor data in highly wooded areas that could be used for classification. Each site also had additional unique objectives that were determined in concurrence with CB&I, the U.S. Army Corps of Engineers (USACE), and project stakeholders during the project planning phase. The objective at both sites was also the knowledge transfer from research organizations (Black Tusk Geophysics [BTG], Acorn Science & Innovation, Inc. [Acorn], Geometrics, and U.S. Naval Research Laboratory [NRL]) to contracting companies such as CB&I.

TECHNOLOGY DESCRIPTION

Both the MM and TEMTADS 2x2 are time domain electromagnetic (TDEM) sensors, making use of three-dimensional receiver coils, with seven and four receiver cubes, respectively. In the larger MM sensor, transverse excitation of subsurface metallic objects is accomplished explicitly with three orthogonal transmitter coils. In the smaller TEMTADS sensor, transverse excitation is accomplished implicitly via the four vertical transmitter coils at offsets from the sensor center.

DEMONSTRATION RESULTS

In general, the primary objectives for Fort Ord were met. CB&I successfully collected high-quality dynamic and cued data using the MM and were able to meet the performance objectives for data quality. All large munitions were correctly classified as TOI. However, one of the large munitions items recovered (155 millimeter [mm] projectile) was classified as a smaller munition as defined for this project. The objective for correctly classifying the smaller munitions was met but the final dig list for the smaller munitions included a high percentage of incorrectly classified non-TOI items.

CB&I successfully collected both dynamic and cued data within heavily wooded areas encountered at Redstone. Four of the blind quality control (QC) seeds were not classified as high confidence TOIs as per the performance objective but were included in the final dig list as “can’t decide” digs. Of the 26 additional TOI items recovered, 19 of these were classified as high confidence TOIs, while the remaining 7 were classified as “can’t decide” digs.

IMPLEMENTATION ISSUES

The most significant implementation issues during both data collection at Fort Ord and RSA were associated with the initial condition of the MM and TEMTADS units when received by CB&I, likely due to the age of both sensor systems during 2014 and 2015 when field work was undertaken. The MM unit required multiple repairs for transmitter boards and wiring. The initial TEMTADS unit from NRL was malfunctioning, and the electronics unit was swapped with a unit recently demobilized by another contractor. During field work at RSA, rain was common, and instructions from NRL staff were to avoid any rain, which created significant delays in initial testing and data collection. At Fort Ord and RSA, complications with data processing software related to the maturity of the software and the experience level of CB&I analysts, which resulted in portions of the data being processed and reviewed after data collection was completed. As a result, immediately administering corrective measures based on QC metrics was not possible.

1.0 INTRODUCTION

In 2007, the Environmental Security Technology Certification Program (ESTCP) started a Pilot Program to validate new technological advances in sensors and software being developed for the detection and classification of Munitions and Explosives of Concern (MEC) for munitions response site remediation. Classification has proven successful at several live sites and the program has expanded to include demonstrations on multiple sites with a wide variety of site conditions and munitions types. The primary benefit of leveraging the new technological advances is an overall reduction in the number of subsurface anomalies that require excavation, resulting in significant cost savings.

CB&I Federal Services LLC (CB&I), working for the ESTCP under Contract No.W912HQ-14-C-0022, performed live site demonstrations at Redstone Arsenal (RSA) located in Huntsville, Alabama, and at the Former Fort Ord located in Monterey County, California (Fort Ord).

1.1 BACKGROUND

The ability to safely and efficiently locate, identify, and remove buried objects on practice and test ranges is critical to the U.S. Department of Defense's mission and its goals of safe operation, sustainability, and environmental stewardship. Although several robust, advanced sensor technologies have been developed for discriminating buried objects on ranges as targets of interest (TOIs), widespread acceptance of the technologies requires that they be demonstrated on live sites, where the impact of operating and data acquisition and analysis parameters can be fully evaluated. The potential benefit of the technology is to reduce the number of subsurface investigations required to remove hazardous MEC in areas where subsurface clearance is required.

Advanced classification (AC) sensors, data processing, and interpretation methods are new technologies gaining momentum for acceptance with regulatory agencies. Acceptance from the regulators will result in classification technologies being used at more clean-up sites, which will result in reduced numbers of excavations, which can ultimately reduce the overall costs of remedial actions.

CB&I collected high fidelity advanced sensor data at Fort Ord and RSA, with the intent to become skilled with AC techniques for both data collection and interpretation. By developing a prioritized dig list, ranging from "high-confidence TOI" to "can't analyze" and "inconclusive" to "high confidence non-TOI," CB&I attempted to demonstrate if AC technologies could significantly reduce the number of expensive excavation of non-unexploded ordnance (UXO) anomalies.

1.2 OBJECTIVES OF THE DEMONSTRATION

The underlying objectives for this project were to collect both dynamic and cued advanced sensor data in varying site conditions and correctly classify all TOIs. Each project site also had specific objectives that were based on site conditions. These objectives included the following:

- Collect dynamic and cued Time-domain Electromagnetic Multi-sensor Towed Array Detection System (TEMTADS) 2x2 data in a highly wooded area at RSA.
- Prioritize the anomaly list for both sites.
- Demonstrate if large munitions, such as 155 millimeter (mm) projectiles to a depth of 60 centimeters (cm), can be confidently classified within the range of background conditions (medium- to high-metallic density) that exist in the Impact Area at Fort Ord.
- Demonstrate if smaller munitions, such as 40mm projectiles, can be confidently classified within the range of background conditions at Fort Ord.
- Use the dig results to determine if the existing Geonics Limited high-sensitivity metal detector (EM61) data may be utilized to determine the existence of large munitions, such as 155mm projectiles at Fort Ord.
- Collect operational data (production and cost) that can be applied to planning future projects at both sites.
- Provide training for project geophysicists in the use of the hardware and classification software, thereby facilitating the transfer of technology from the researchers to production companies.
- Provide data that will assist in gaining regulatory acceptance of the AC technologies.

1.3 REGULATORY DRIVERS

In general, AC sensors, data processing, and interpretation methods are new technologies gaining momentum for acceptance with regulatory agencies. Acceptance from the regulators will result in classification technologies being used at more clean-up sites, resulting in reduced numbers of excavations, which can ultimately reduce the overall costs of remedial actions.

The Munitions Response Program at RSA is conducted under the oversight of the Alabama Department of Environmental Management (ADEM). ADEM is familiar with AC sensors, data processing, and interpretation methodology, and welcomed the demonstration in RSA site conditions.

MEC removal in Units 11 and 12 at the former Fort Ord is being conducted in accordance with the Final Track 3 Record of Decision (ROD), Impact Area Munitions Response Area, Track 3 Munitions Response Site, Former Fort Ord, California (U.S. Department of the Army [Army], 2008). The general remedial action objective is to manage "the potential risk to future land users from MEC at the Impact Area MRA." Surface removal in Units 11 and 12 has been completed. Subsurface removal may be required in some areas in the future depending on proposed land use.

The munitions response program at Fort Ord is conducted under the oversight of the California Department of Toxic Substances Control (DTSC) and the U.S. Environmental Protection Agency. These agencies are familiar with AC sensors, data processing, and interpretation methods, and were receptive of the demonstration at Fort Ord.

2.0 TECHNOLOGY

2.1 METALMAPPER (MM)

The MM is an advanced time-domain electromagnetic (TDEM) sensor designed specifically for classification of MEC items. This system is a unique and innovative design due to the following:

- The antenna platform includes three mutually orthogonal transmitter loops and a spatial array of seven 3-axis receiver antennae (21 independent measurements of the transient secondary magnetic field).
- The system includes an Electronically Switched TDEM Transmitter Loop Driver. The system is able to control the source and receiver combinations. Under control of the data acquisition computer, the output of the transmitter can be directed to any single loop or automatically multiplexed between loops. The data acquisition computer also controls of the fundamental waveform period, duty cycle, and pulse polarity. Depending on the survey mode (e.g., static or dynamic), the fundamental frequency of transmission can be varied over the range 1.11≤f ≤810 hertz (Hz).

The system design allows the MM to interrogate the subsurface object from a variety of angles and distances and subsequently perform advanced analysis of the received signals to provide quantitative information on the shape and electrical properties of the object. **Figure 2-1** presents a schematic of the system.

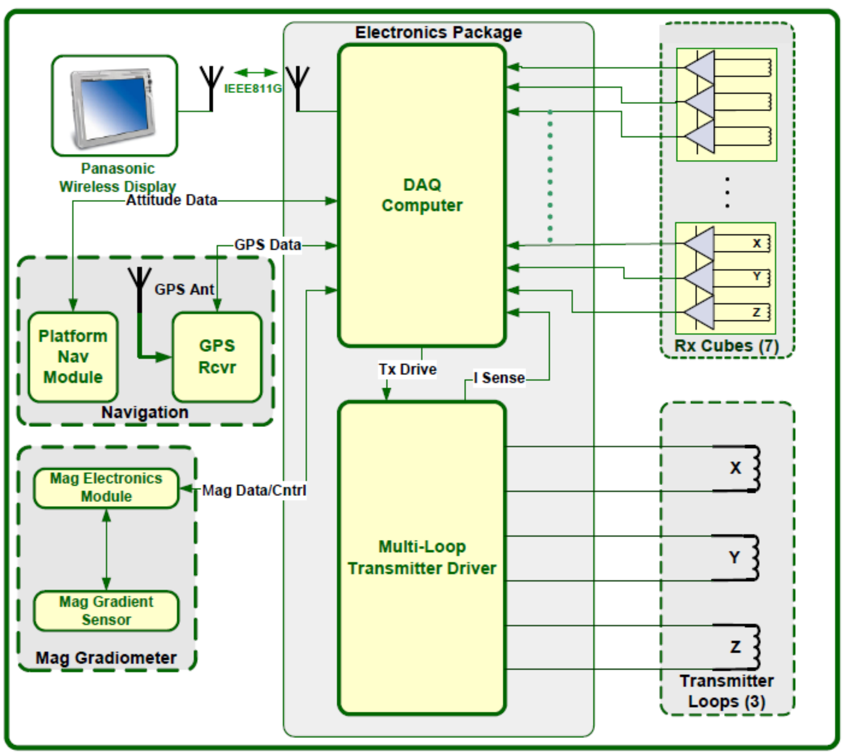

Figure 2-1. MM System Schematic Integrated with a Global Positioning System (GPS) and Inertial Measurement Unit (IMU)

Instruments for TDEM data collection in both dynamic and cued mode included a Geometrics MM (SN 1006) provided by USACE, Sacramento District, combined with a Leica GS15 Real-time Kinematic (RTK) GPS. This equipment was deployed on a skid behind a bulldozer for dynamic data collection (**Figure 2-2**) and a skid mounted in front of a Bobcat® T300 for cued data collection (**Figure 2-3**). Both configurations were designed for efficiency and high-quality data collection.

Figure 2-2. MM Configured for Dynamic Data Collection with Bulldozer

Figure 2-3. MM Configured for Cued Data Collection with Bobcat

2.2 TEMTADS

The TEMTADS is an advanced TDEM sensor designed specifically for classification of MEC items. This system is built from polyvinyl chloride (PVC) and fiberglass, and the receivers are mounted on a wheeled cart. The positioning sensor rests on a five-legged platform above the center of the system. The data-acquisition computer and electronics are mounted in the operator's backpack.

The center-to-center distance of the sensors is 40 cm in both the x and y directions. The array size is 80 cm by 80 cm, and is deployed on a set of wheels so that the sensors are 20 cm above the ground. The transmitter electronics and the data acquisition computer are mounted in the operator backpack. A second person runs the control software over a wireless connection to a tablet. There are two modes of operation: dynamic and cued modes. Data collection is controlled in dynamic mode using G&G Science Co., Ltd.'s EM3D© application suite in dynamic mode. In cued mode, data collection is performed with U.S. Naval Research Laboratory (NRL) software.

Decay data are collected at a rate of 500 kilohertz (kHz) after turn-off of the excitation pulse for up to 25 milliseconds (ms). This results in a raw decay of up to 12,500 points, which are grouped into logarithmically-spaced "gates" with center times ranging from 25 microseconds (µs) to 24.35 ms with proportional widths. The data are saved to disk.

The design allows the TEMTADS to interrogate subsurface objects from a variety of angles and distances, and subsequently perform advanced analysis of the received signals to provide quantitative information on the shape and electrical properties of the source object.

Instruments for TDEM data collection at RSA in both dynamic and cued mode included a TEMTADS provided by NRL, combined with a Trimble® S7 Robotic Total Station (RTS). This equipment was deployed on a man-operated cart for both dynamic data collection and for cued data collection. **Figure 2-4** shows the TEMTADS with an RTS prism, elevated to avoid the instrument operator obstructing the laser, and inertial measuring unit (IMU). A schematic of the electromagnetic (EM) induction sensor array showing the position of the four sensors is also illustrated. The orientation of the sensor cubes are indicated relative to the forward direction of travel.

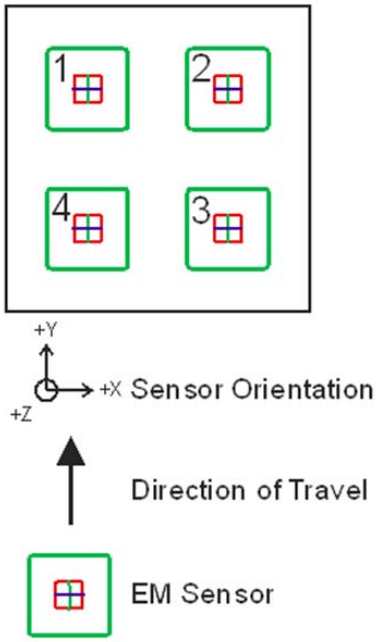

Figure 2-4. TEMTADS with RTS Navigation and Hardware Schematic

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Current AC survey instruments include the MM, TEMTADS, Man Portable Vector (MPV), and the Berkley UXO Discriminator (BUD). At the time of planning the demonstration, the main advantage of the MM was that it was commercially available, while the others had limited availability and were used primarily as research instruments.

Advantages of the AC instrumentation are as follows:

- They use a multi-transmitter/receiver system so that a target is illuminated from multiple directions simultaneously, yielding better detection resolution than EM61s.
- Dynamic data are used for detection and may be used for classification in a single data collection event.
- Flexibility to set window lengths and number of readings for stacking allows for customization of equipment setup parameters and optimization of the survey based on the expected TOIs at a given depth within an expected anomaly density.
- Cued data are high fidelity and produce high-quality and accurate inversions for anomaly classification.
- Library matching tools allow for quick, easy, and reliable classification of anomalies.

Limitations of the AC instrumentation include the following:

- Dynamic data collection is typically slower and therefore can be more expensive than conventional EM61 surveys.
- Cued data collection requires a previous dynamic survey (either conventional digital geophysical mapping [DGM] or AC sensor) to detect anomalies, resulting in increased geophysical survey costs (although often realized in savings of excavation costs).
- At the time of this project, the current libraries were incomplete and may require the addition of TOI data.
- The MM is large and cumbersome. The current system at the time of this data collection event was heavy and difficult to maneuver where there were terrain and vegetation issues.
- The TEMTADS is 80 cm by 80 cm and mounted on a cart, so areas where access is limited due to terrain or vegetation density may be an issue.
- Both the MM and the TEMTADS are not designed for rugged terrain.

3.0 PERFORMANCE OBJECTIVES

Data collection and analysis performance objectives for Fort Ord using the MM, and for RSA using the TEMTADS, are presented in **Table 3-1**. More information about the evaluation of these objects can be found in the demonstration reports for each site.

Table 3-1. Performance Objectives

Performance Objective	Metric	Data Required	Success Criteria
Data Collection Objectives (MetalMapper)			
Instrument verification strip (IVS) Repeatability	Location and detection amplitudes are repeatable	Dynamic and cued IVS data	Detection amplitudes are within 25%, Locations are within 0.5 meters (m).
Dynamic data full-coverage survey	Across-track line separation Along-line data separation	Dynamic data	90% Across-track separation are within 0.5 m. 100% are within 1.0 m. 95% Along-line data separation are within 15 cm. 100% are within 20 cm.
TOIs detection	Detection of seed items	Dynamic data	100% of seed items detected.
Cued data location	Distance between cued location setup and the inverted location	Cued data	Locations within 40 cm.
Data Collection Objectives (TEMTADS 2x2)			
IVS repeatability	Location and detection amplitudes are repeatable	Dynamic and cued IVS data	Dynamic: Detection amplitudes are within 25%. Locations are within 0.25 m. Cued: Library match to initial polarizabilities metric ≥0.90 for each set of three inverted polarizabilities. All IVS items fit locations within 0.25 m of ground truth locations
Dynamic data full-coverage survey	Across-track line separation Along-line data separation	Dynamic data	90% across-track separation is within 0.5 m. 100% are within 0.7 m. 95% along-line data separation is within 15 cm. 100% are within 20 cm. Metrics exclude obstructed areas.
TOI detection	Detection of seed items	Dynamic data	100% of seed items detected.
Cued data location	Distance between cued location setup and the inverted location	Cued data	Locations within 40 cm.
Data Analysis Objectives (MetalMapper)			
Correctly classify TOIs	Identify TOIs and seed items	Cued data Excavation results	100% of seed items correctly classified. Correctly classify 75% of small TOIs and 100% of large TOIs for each density region.
Correctly classify non-TOIs	Eliminate false alarms	Cued data Excavation Results	65% of non-TOIs correctly classified

Table 3-1. Performance Objectives (Continued)

Performance Objective	Metric	Data Required	Success Criteria
Minimize “can’t analyze” anomalies	High-quality cued data	Cued data	<15% “can’t analyze” anomalies
Correctly place the stop-dig threshold	TOIs above stop-dig threshold	Prioritized dig sheet Excavation Results	No large TOIs below threshold. Correctly classify 75% of smaller TOIs. Minimize non-TOI digs above threshold.
Correct anomaly location	Anomaly locations on dig list are accurate.	Detection, inversion, and excavated locations	Detected location and inversion location are within 40 cm. Excavated location is within 40 cm of inversion location.
Data Analysis Objectives (TEMTADS 2x2)			
Correctly classify TOIs	Identify TOI and seed items	Cued data and excavation results	100% of seed items correctly classified. Correctly classify 100% of TOIs.
Correctly classify non-TOIs	Eliminate false alarms	Cued data and excavation results	70% of non-TOIs correctly classified.
Minimize “can’t analyze” anomalies	High-quality cued data	Cued data	<5% “can’t analyze” anomalies.
Correctly place the stop-dig threshold	TOIs above stop-dig threshold	Prioritized dig sheet and excavation results	No TOI below threshold. Minimize non-TOI digs above threshold.
Correct anomaly locations	Anomaly locations on dig list are accurate.	Detection, inversion, and excavated locations	Detected location and inversion location are within 40 cm. Excavated location is within 25 cm of inversion location.

4.0 SITE DESCRIPTIONS

Demonstration locations for this project include sites at Fort Ord and RSA.

4.1 SITE LOCATION AND HISTORY

Sites designated 12-A, 12-B, 11-A, and 11-B within burn units 11 and 12 were chosen at Fort Ord with target density generally increasing to the east as shown in Figure 4-1. A variety of MEC types were found on the surface and a similar variety were expected in the subsurface. The site presented challenging conditions in terms of high metallic density but also included areas of moderate density that allowed evaluation of a range of conditions.

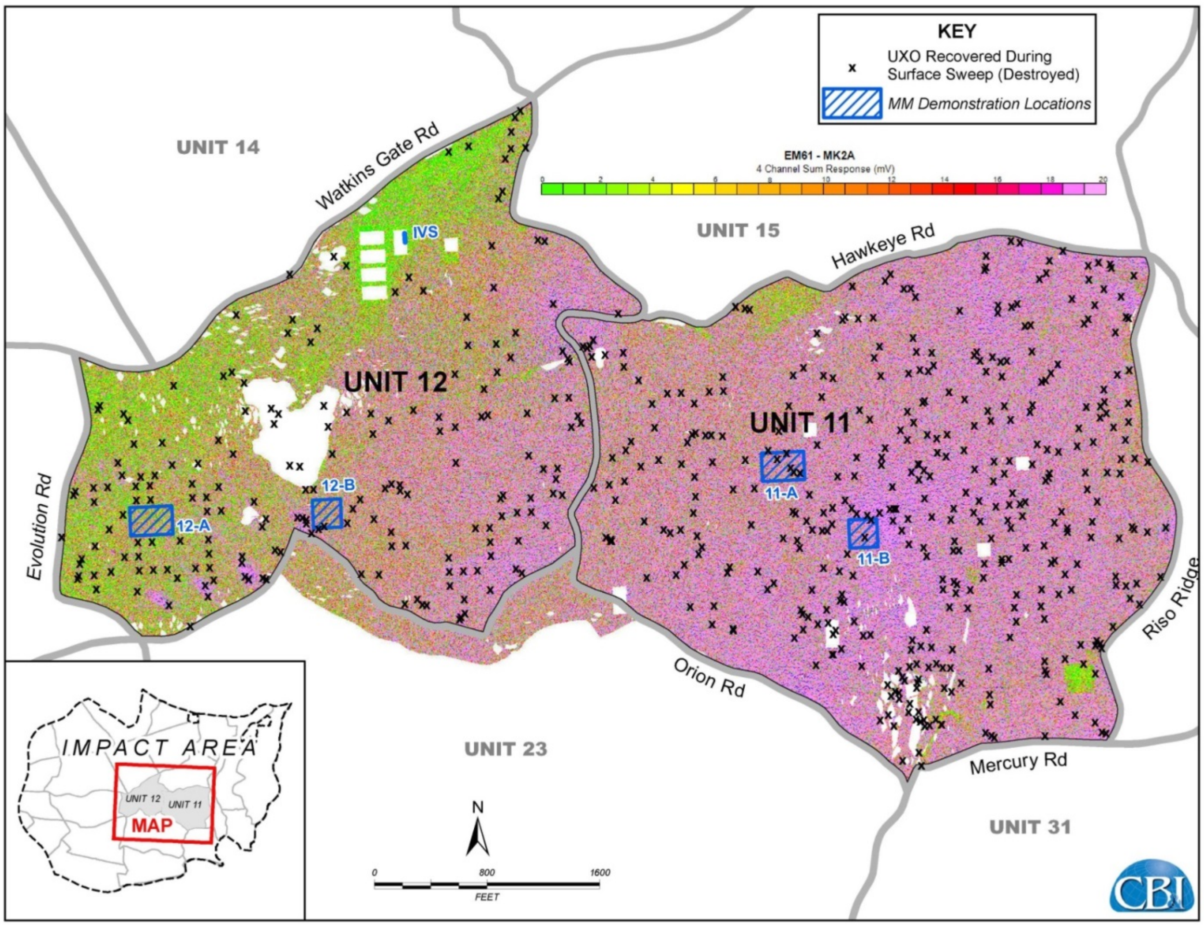

Figure 4-1. DGM and Surface Removal Results

RSA Site 073 (RSA-073) within the larger Site RSA-312 was chosen as a testing area for the TEMTADS 2x2 (Figure 4-2). The site presented challenging conditions in terms of a wide range of vegetation density and canopy as seen in Figures 4-2 and 4-3.

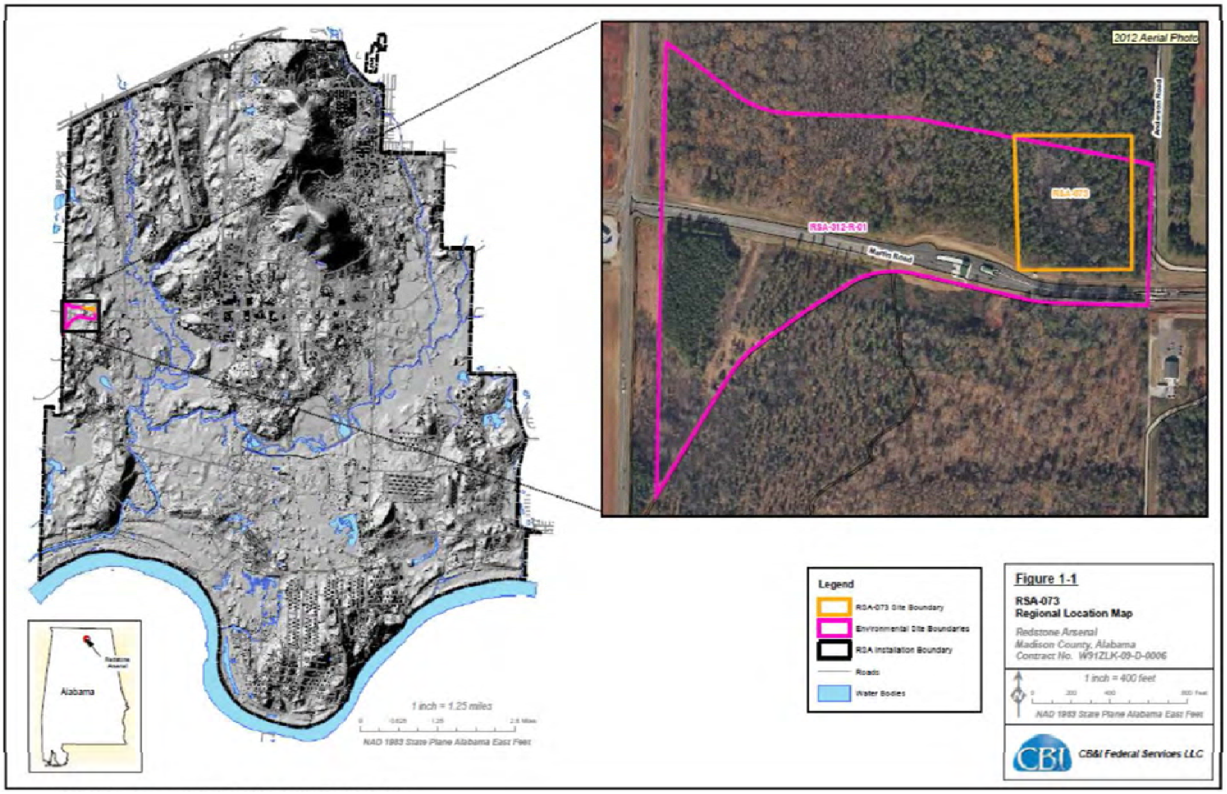

Figure 4-2. Location of Site RSA-073

Figure 4-3. Tree Coverage Typical of Site RSA-073

4.2 SITE GEOLOGY

Fort Ord is within the Coast Ranges Geomorphic Province. Fort Ord is underlain by the following units: Mesozoic granitic and metamorphic rocks, Miocene marine sedimentary rocks of the Monterey Formation, and Upper Miocene to Lower Pliocene marine sandstone of the Santa Margarita Formation. The units are overlain by younger sediments, which may include: Plio-Pleistocene alluvial fan, lake, and fluvial deposits of the Paso Robles Formation; Pleistocene eolian and fluvial sands of the Aromas Sand; Pleistocene to Holocene valley fill deposits consisting of poorly consolidated gravel, sand, silt, and clay; and Pleistocene and Holocene dune sands. Outcrops and near surface rocks can include the Santa Margarita Formation, which potentially poses the most geophysically-challenging geology because the sandstone has an iron rich matrix. However, this formation did not have a significant impact on the EM61 surveys and CB&I did not observe a significant impact on the MM surveys.

Generally, Tuscumbia Limestone (bedrock) and associated overburden residual soil underlie RSA. The rocks underlying RSA are primarily from the Mississippian Age and consist of (in ascending order) Chattanooga Shale, Fort Payne Chert, Tuscumbia Limestone, Monteagle Limestone, Pride Mountain Formation, Hartselle Sandstone, and Bangor Limestone. Dissolution of the Tuscumbia Limestone has formed large caves, caverns, springs, and openings that have caused sinkholes and depressions on the surface. The Chattanooga Shale is approximately 198 feet (ft) below ground surface (bgs) (Malcolm Pirnie, Inc., 2008). Soil is typically cherty silt loams and silty clay loams. In northern RSA, the soil correlates well with the bedrock, where approximately 40–50 ft of red, sandy clay residual soil overlie limestone and narrow lenses of sandy, poorly drained soil. Residual soil at RSA is derived from limestone and consists of sandy clay, chert, and limestone fragments in a clay matrix. Significant deposits of alluvial and colluvial materials (clays, silts, sands, and gravel) are typically confined to the lowlands at RSA.

4.3 MUNITIONS CONTAMINATION

Since 1917, portions of former Fort Ord were used by cavalry, field artillery, and infantry units for maneuvers, target ranges, and other purposes. From 1947 to 1974, Fort Ord was a basic training center. After 1975, the 7th Infantry Division occupied Fort Ord. Military munitions were fired and used on the facility, including artillery and mortar projectiles, rockets and guided missiles, rifle and hand grenades, land mines, pyrotechnics, bombs, and demolition materials.

Surface sweeps identified MEC items throughout Units 11 and 12, including 37mm, 40mm, 57mm, 60mm, 75mm, 90mm, 105mm, 155mm, and 8-inch (in) projectiles. The results of the DGM indicate that a variety of MEC items may be present in the subsurface. The Base Realignment and Closure (BRAC) Office was interested in determining if AC methods can be used to locate large MEC items such as 155mm projectiles, as well as sensitive munitions such as 40mm projectiles in areas of increasing metallic signature density as shown in Figure 4-3.

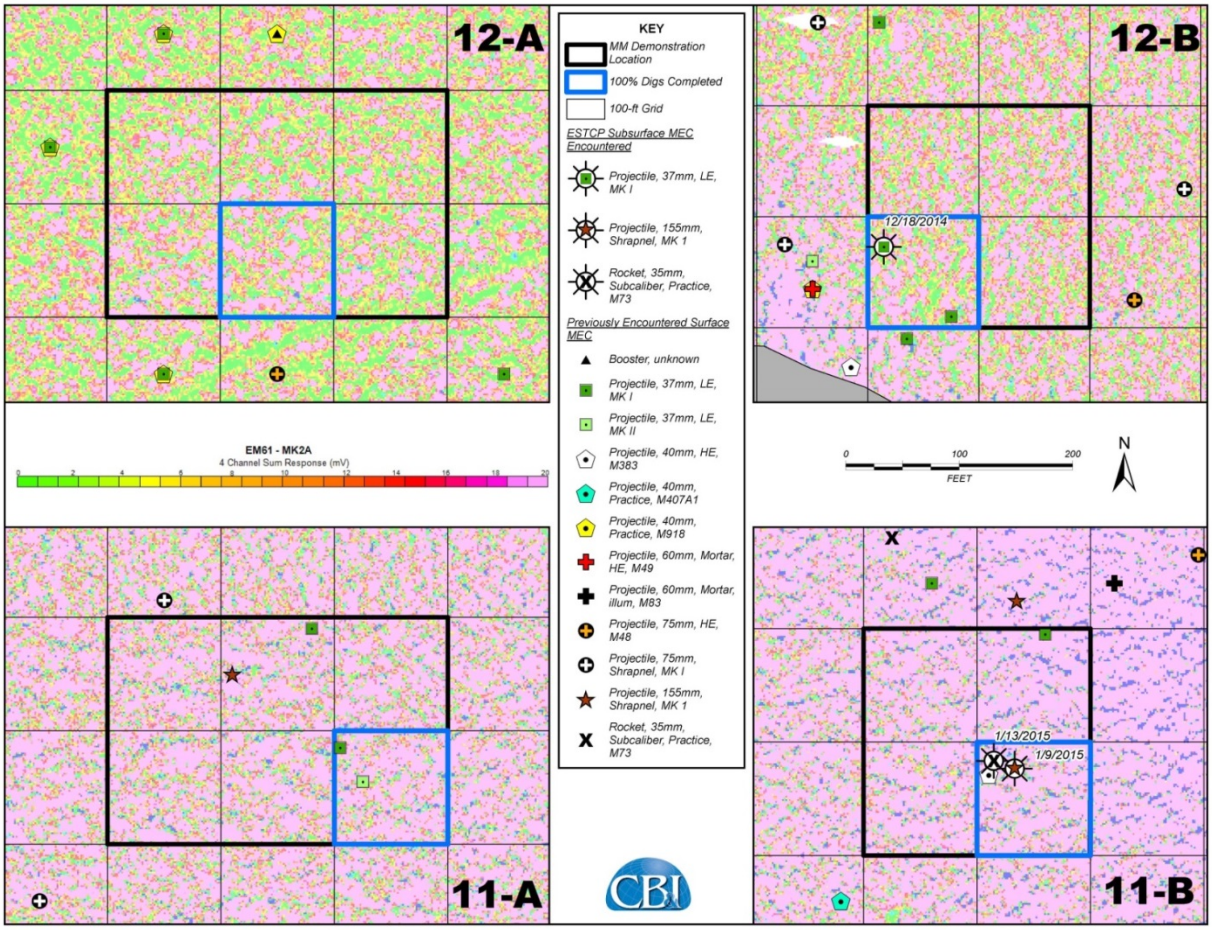

Figure 4-4. EM61 Data at MM Survey Areas in Units 11 and 12.

At RSA, areas east of Anderson Road were used for explosives training and munitions testing and as impact areas for 4.2-in mortars, large caliber projectiles (75mm–155mm), and numerous types of bombs. With the exception of some areas north of Site RSA-312 and former Site RSA-073, the majority of the areas west of Anderson Road to the RSA boundary were safety/buffer zones. A review of available historical photographs identified only limited activities occurring in areas west of Anderson Road. Site RSA-073 is not a known impact area; however, land scarring/craters are visible in Site RSA-073 in the Light Detection and Ranging dataset. The MEC reportedly used at Site RSA-073 includes AN-M76 bombs, PT1 (incendiary mixture similar to “goop”)-filled; M47-type bombs, Isobutyl Methacrylate Incendiary Mix (IM-AE)- and napalm-filled; M69 bombs, IM-AE-filled; 155mm white phosphorous (WP) projectiles; 8mm WP projectiles; 105mm WP projectiles; 155mm titanium tetrachloride (FM) projectiles; 75mm FM projectiles; 81mm high explosive (HE) projectiles; 40mm HE projectiles; and M5 bursters.

5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

At both Fort Ord and RSA, the intent was to find larger MEC at depth: 155mm projectiles buried to 60 cm at Fort Ord, and 4.2-in mortars at depths up to 90 cm at RSA. However, CB&I attempted to classify all TOIs correctly and thereby show that a reduction of the number of unnecessary digs of non-TOIs is possible.

Given the wide variety of possible munitions at Fort Ord and that the area is considered to have a very high anomaly density, CB&I sought to demonstrate whether large munitions, such as 155mm projectiles, could be confidently classified in a challenging environment with high metallic background. In order to determine if this was possible, areas of relatively high, medium-high, medium, and low anomaly densities were surveyed in both dynamic and cued mode for detection and classification respectively.

The study area consisted of low- and medium-density areas located in Unit 12, 12A, and 12B, respectively, and a high-density area consisting of two locations in Unit 11, 11A, and 11B. All six areas were chosen based on the previous EM61 surveys and their proximity to MEC items found during previous surface removal operations. One grid from each location was chosen for a 100% investigation of all MM targets detected during the dynamic survey. Intrusive investigation of targets in the remaining grids was limited to targets with a high confidence of being TOI based on Black Tusk Geophysics (BTG) inversion results obtained from the dynamic MM data. In addition, targets were selected from outside the study area from anomalies present in the existing EM61 data. These additional EM61 targets were investigated to demonstrate the effectiveness of using existing EM61 data during the detection phase, with follow-up MM cued measurements used for classification. The targets were selected using a threshold of 146 millivolts (mV) on Channel 2 based on the published NRL response value for a 155mm projectile in the least favorable orientation (horizontal).

At Site RSA-073, there is a wide variety of possible munitions and the area is considered to have a medium-to-high anomaly density as well. The goal of CB&I was to demonstrate whether large munitions, such as 4.2-in mortars at a depth of approximately 90 cm, could be confidently classified in a challenging environment such as this. The task was also made more challenging by the moderately dense vegetation, and noisy site conditions for EM systems. Site RSA-073 was surveyed in both dynamic and cued mode for detection and classification. Intrusive investigations were performed as part of a larger investigation at RSA-312, which included 221 digs in Site RSA-073.

Data from both sites were processed to generate models of each target, and ranked dig lists for each individual site. Two dig lists were developed for Fort Ord: one for large TOI such as 155mm projectiles and large industry standard objects (ISOs), the second for all TOI as small as 20mm projectiles. These lists were scored by ESTCP based on ground truth information provided by CB&I dig teams to ESTCP, but blind to the CB&I and BTG data analysts. At RSA, the dig list was self-scored.

5.2 SITE PREPARATION

The sites at Fort Ord and RSA all had prior brush cutting and EM61 DGM. The following site preparation activities were performed in preparation for ESTCP data collection:

- Vegetation within the interior of these units was cleared.
- Debris, including general metallic debris, was removed.
- Grid systems were reestablished with the verification of and replacement of corner nails.
- Quality control (QC) and quality assurance (QA) seeds (described below) were placed and documented.

At Fort Ord, CB&I seeded the site using small, medium, and large ISOs in the low- and medium-density grids and large ISOs in the high-density grids. Inert items including 37mm, 40mm, 57mm, 75mm, and 155mm projectiles were included among the blind seeds. There were two seed items per 100 ft x 100 ft subgrid: a CB&I QC seed and an ESTCP QA seed.

At RSA, seeded items included small, medium, and large ISOs, in addition to inert 37mm, 40mm, and 75mm projectiles, and 81mm and 4.2-in mortars.

Information including the item type, depth, and location was documented using an RTK GPS or RTS and the azimuth and inclination was recorded.

5.3 SYSTEM SPECIFICATION

The MM and TEMTADS system designs as used in these demonstrations are described in Section 2 of this report.

At Fort Ord, dynamic data were collected with the MM deployed on a skid behind a bulldozer. This is similar to DGM surveys conducted by CB&I at Fort Ord where EM61 sensors have been mounted behind a tow vehicle. The MM averages GPS readings while the EM data are being collected. GPS and IMU data were collected at 10 points per second and the coordinates stored with the data are either the most recent fix, or the average of fixes received during the data point collection interval. The EM3DAcquire software could not make use of Global Navigation Satellite System (GLONASS) National Marine Electronics Association strings, which triggered constant GPS quality warnings, so that feature was disabled in the GPS unit.

Being smaller and lighter, the TEMTADS system used at RSA was used in standard form on a wheeled cart. The positioning sensor rests on a five-legged platform above the center of the system, and in order to avoid any line-of-site obstructions created by the operators, additional stand-offs were added, as shown in Figure 2.4. The data acquisition computer and electronics are mounted in the operator’s backpack and controlled via a tablet over a wireless connection. The RTS streams pseudo-National Marine Electronics Association data to the TEMTADS, similar to a GPS. Transmitter switching and receiver sampling is controlled by programmable hardware. In dynamic mode data collection was accomplished with EM3DAquire software, while in cued mode NRL software specific to the TEMTADS was used for data acquisition.

Decay data were collected at a rate of 500 kHz after turn-off of the excitation pulse for up to 25 ms, as indicated with the *HoldOff* parameter. The raw decay measurements are grouped into logarithmically-spaced time gates with center times ranging from 25 μs to 24.35 ms with proportional widths. Responses within a specific time gate are averaged and become the value of the signal for that time gate. The widths of the gates are determined by the *GateWidth* parameter and are specified as a percentage, e.g., the width of a gate at 600 μs would be 60 μs with a gate width of 10%.

5.4 DATA COLLECTION

5.4.1 MetalMapper Data Collection at Fort Ord

At Fort Ord, CB&I collected approximately five acres of dynamic MM data, which spanned high-, medium-high-, medium-, and low-density areas. Prior to data collection, three different sets of time gates with maximum values of 22.5 ms, 8.3 ms, and 2.7 ms were tested in both the instrument verification strip (IVS) and portions of the low- and high-density areas. Analysis by BTG indicated that using a longer time gate (22.5 ms) provided better detection capabilities without affecting dynamic data quality. Dynamic data were acquired over 29 time gates ranging from 0.024 ms to 22.5 ms, but only those between 0.208 ms and 22.5 ms were used for analysis due to inherent noise in the earlier time gates.

The dynamic survey mode consisted of complete coverage within areas 11A, 11B, 12A, and 12B. Data were collected along parallel transects with 0.75 m nominal line spacing. Sample rate and survey speeds were slow enough to ensure down-line spacing of <15 cm. Survey positions were recorded and logged using a RTK GPS.

A total of 2,653 anomalies identified in the dynamic data plus 150 targets identified from EM61 data were investigated with the MM in cued mode. These data were used for classification into TOI, non-TOI, and “can’t analyze” groups. All 2,803 targets cued with the MM were investigated intrusively for subsequent validation. Cued data were acquired over 52 time gates ranging from 0.11 ms to 23.75 ms with number stacks set to 10. Cued mode data were collected over each identified anomaly, with measurements repeated as necessary due to offsets of the sensor relative to the anomaly source or other data quality issues. In-field QC software from White River Technologies was used to reduce the number of recollects at a later date, and indicated to the field team when it was necessary to move the sensor for a second measurement.

Given the large quantity of metallic items in the ground, especially in the Unit 11 grids, background locations were created adjacent to each grid by mechanically removing the upper foot of soil under the supervision of UXO support personnel. This was performed at locations immediately adjacent to each of the four grids selected for investigation.

5.4.2 TEMTADS Data Collection at RSA

CB&I collected approximately 8.21 acres of dynamic data from Site RSA-073. Dynamic surveying activities consisted of complete coverage of accessible areas in the designated survey area. Data were collected along parallel transects with 0.4-m nominal line spacing with some deviation from a straight line path due to obstructions. Sample rate and survey speeds were slow enough to ensure >90% of down-line spacing was <15 cm and 100% of down-line spacing was <20 cm.

A total of 14,873 anomalies were identified in the dynamic data using a threshold of 1.4 mV per Ampere (mV/A). Due to time and budget constraints and the fact that the TEMTADS was only available until the end of March 2016, a subset, including 1,178 targets, was chosen for cued investigation. The cued mode data collection consisted of surveying static data over the subset of anomalies identified from the dynamic survey. Cued data were collected over each identified anomaly using acquisition software from NRL, with measurements repeated as necessary due to offsets of the sensor relative to the anomaly source or other data quality issues.

5.5 DATA QUALITY CHECKS

During data collection with the MM and TEMTADS instruments, testing at the IVS was performed prior to and following data collection each day that weather and other circumstances permitted. Data were evaluated against known item locations, responses, and inverted polarizabilities. Additionally, the positioning systems (RTK GPS or RTS) were checked against known survey locations to verify functionality.

Sensor function tests were performed, where a small-schedule 80 ISO was placed in a jig, and cued measurements taken. Response amplitudes were verified for all monostatic transmitter and receiver pairs against a reference response. At Fort Ord, an ad hoc sensor function test was used, where a small schedule 80 ISO was centered at the base of the coils, and inversion results were matched against library polarizabilities.

At RSA, background validation tests were performed, to ensure each background used for cued data corrections was sufficiently free of metal to provide good match metrics for site TOIs. At both sites, backgrounds were rejected that indicated possible metallic signatures.

Quality checks were performed for all cued measurements. These included comparing target location and inversion results to those recovered during intrusive investigations. The measurement quality objectives (MQO) along with the testing frequencies, acceptance criteria, and failure response are presented in the demonstration reports for each site.

5.6 VALIDATION

All of the targets in the four grids selected for BRAC's treatability study at Fort Ord were excavated. An additional 150 targets in Unit 11 were selected from EM61 data for investigation with the MM. All 150 of these anomalies were dug as well. Each item encountered was identified, photographed, depth was measured, its location determined using centimeter-level GPS, and the item removed if possible.

At Site RSA-073, a subset of 221 targets was intrusively investigated during corresponding activities throughout Site RSA-312. Each item encountered was identified and photographed. For items recovered during the intrusive investigation of a target, depth was measured, and its location determined using centimeter-level RTS. Recovered items were removed for disposal when possible.

ESTCP's Intrusive Investigation Data Collection Instructions were followed in accordance with the ESTCP demonstration plans for both sites.

6.0 DATA ANALYSIS AND PRODUCTS

The processing and analysis steps that were used to categorize targets and create a ranked dig list are described below.

6.1 PREPROCESSING

For both the MM and TEMTADS, raw data were collected and stored as .TEM files. Pre-processing of the raw .TEM files included correcting for background values, and converting the points from the geographic coordinate system used for collection to the appropriate Universal Transverse Mercator (UTM) coordinate system used for processing. The resulting data were exported to CSV files for import into UXOLab and UX-Analyze.

Since these are multi-static sensors, each component of each receiver cube was filtered and leveled individually. Dynamic MM data were leveled using a de-trend function with a window length of 20 m. Cued data had any spikes removed with a custom de-spike tool in UXOLab. For TEMTADS dynamic data, a UCEdrift non-linear filter was used to level the data with a low of 20, high of 0, and window of 10 seconds.

Given the tree density of the test area at RSA, optical shadows between RTS and the prism were minimized as much as possible. Positioning information was interpolated linearly between valid positions for detection survey data.

6.2 TARGET SELECTION FOR DETECTION

At Fort Ord, target selection was performed on MM data collected in dynamic mode in grids 11A, 11B, 12A, and 12B. The MM detection thresholds were determined during initial IVS and test pit data collection in conjunction with measurements of noise in the high-density (11B), and medium-density (12B) grids. In subgrids 11A SE, 11B SE, 12A NC, and 12B SW, all anomalies over the target threshold were selected for investigation. Target selection was performed using an along-profile picking routine on data from the five central-most receiver cubes, with a minimum separation between targets of 0.5 m. The picking threshold was set at 0.35 mV/A for a stack of time gates 13–16. Outside of these subgrids, the same target picking was performed, but targets were then prioritized by the match of their inverted polarizabilities to those of items in the ordnance library developed at the test pit and analysis of UXO-like features present in their polarizabilities.

An additional 150 targets in Unit 11 were selected from previously collected EM61-MKII data based on response and proximity to existing grids and the size of the anomaly, and with minimum response of 146 mV on Channel 2. This was determined to be the response of a 155mm projectile at 60 cm depth with the least favorable orientation. Cued data were collected on all of these targets.

At RSA, target selection was performed on gridded, dynamic TEMTADS monostatic data in the z (vertical) direction. The detection threshold was set at 1.4 mV/A on Channel 5 (0.137 ms), which corresponded to the modeled response of a horizontal 4.2-in mortar at depth of 3 ft.

A secondary threshold was applied at 3.25 mV/A on Channel 5, approximately five times the root mean squared (RMS) background noise level. This resulted in an anomaly list for cued interrogation of targets with sufficiently high signal allowing for consistent and reliable inversions. For the majority of full 100-ft x 100-ft grids, 47 targets above the 3.25 mV/A threshold were randomly selected by the data processors, and the QC and QA geophysicists selected additional anomalies potentially as low as a 1.4 mV/A threshold for a total of approximately 50 targets per grid.

6.3 PARAMETER ESTIMATES

Cued MM records for each of the detected anomalies were imported into UXOLab, and inversions were performed to generate information on the source location and polarizabilities. Both single and multi-target models were fitted during the inversion process up to a maximum of three dipole solutions for a total of six models. These data and models were analyzed using the QCZilla routine in UXOLab, where the analyst reviewed polarizability profiles for each record in conjunction with the amplitude and spatial attributes, inversion model fit, and geometry. Modeled polarizabilities were compared against a library of polarizabilities and categorized based on the UXOLab misfit metric. Cued TEMTADS records for each of the detected anomalies were processed and modeled in a similar fashion with the UX-Analyze module of Oasis montaj. Differences included automation of the selection of the best model for a given target from single and multisource solutions, and a match metric with a different measure of misfit between modeled and library polarizabilities.

6.4 CLASSIFIER AND TRAINING

Dig list development was accomplished using BTG’s Digzilla tool at Fort Ord, which is designed to automate the prioritization of the dig list. Using this tool, the analyst was able to interactively prioritize anomalies using various parameters such as polarizability misfit and quality, decay, relative size, analyst notes, and other related attributes. Comparisons between the measured targets and the library data were performed using an equal weight for all three primary polarizabilities.

For RSA, dig-list development was performed using Geosoft Inc.’s UX-Analyze classification and ranking tools. Classification and ranking used the UX-Analyze decision statistic, an averaging of library matching results across multiple polarizability combinations. The analyst was able to interactively refine the prioritization using various parameters such as polarization plots, decay, relative size, analyst notes, and other related attributes.

For data from Fort Ord, cluster analysis was used to find any unexplained anomalies. Training data were then selected by visual inspection of estimated features. Models passed by the analyst from the inversion were displayed on a feature plot with the decay on the y-axis and relative size on the x-axis along with the library reference items. Anomalies that clustered close to the library reference items were evaluated further in terms of the similarity of their polarizabilities to those of the known TOIs. During the analysis and evaluation process, other clusters (or populations) of anomalies were identified, which exhibited UXO-like polarizabilities, signal amplitude, and decay properties.

Training digs information was not used as part of the RSA project, and instead a single dig list was developed.

For Fort Ord, CB&I analysts requested ground truth for feature vectors that plotted between clusters of TOIs and non-TOIs in order to determine the extents of the distributions of TOI features. CB&I analysts also requested ground truth for non-TOIs, rather than assume that test feature vectors with a large misfit to known TOIs polarizabilities are non-TOIs. CB&I analysts requested ground truth for a total of 84 targets. At RSA, classification was done in a single iteration, and while no training data was given to the analyst, training digs were still added to the dig list.

6.5 DATA PRODUCTS

The following data were delivered as part of the Fort Ord and RSA demonstrations:

Background Data: Raw and pre-processed background data files were provided along with their locations.

Dynamic and Cued Data: Raw and pre-processed data were provided. The pre-processed data had coordinates converted to the appropriate UTM zone and corrected for pitch, roll, and yaw, and background removed.

Dynamic and Cued Inverted Data (Fort Ord): UXOLab .mat files containing the inverted and pre-modeled data were provided for Fort Ord.

Cued Inverted Data (RSA): UX-Analyze project files containing the inverted and pre-modeled data in the form of .gdb files. Additionally, decision plots generated by UX-Analyze were delivered for cued data.

Initial Anomaly Lists: Initial anomaly lists included lists of all anomalies detected above threshold in the dynamic data, and in the case of RSA, anomalies selected for further investigation in cued mode.

Final Classification Dig List (Fort Ord): The final classification dig list for Fort Ord included the prioritized anomaly list with all anomalies classified. Two dig lists, one based on large TOIs (TOI 1) and one for all TOIs (TOI 1 and TOI 2) were generated.

Final Classification Dig List (RSA): The final classification dig list for RSA included the prioritized anomaly list with all anomalies classified.

Intrusive Investigation Results: Photos, field notes, positions, and depths of metallic objects recovered from the intrusive investigation were provided for targets investigated at both project sites.

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7.0 PERFORMANCE ASSESSMENT

The performance objectives and results of this project are summarized in the following sections.

7.1 IVS REPEATABILITY

During MM dynamic testing at Fort Ord, IVS item amplitudes were within 25% of reference values, with three exceptions resulting from inconsistent line paths over the seed items. Seed items 1 and 2 passed cued data tests at the IVS locations. The final eight tests for seed item 3 had location offset failures with a maximum 0.56 m and a median 0.54 m offset. The final test for seed item 5 had a location offset failure of 0.53 m.

t RSA, during dynamic test with TETMTADS at the IVS, all detection amplitudes were within 25% of the average response of the first five tests for each of the four items. More than 99% of IVS item locations were within 0.25 m, with seven outliers.

Initial matches over 0.9 were obtained for three of the four IVS items, while one low initial match appeared to be the result of sensitivity to the background correction. Ongoing matches based on addition to the polarizability library, were all >0.87. The derived positions of three IVS items were within 0.25 m of ground truth for all cued measurements. Item 3 was outside of the 0.25-m metric during all cued tests, possibly the result of an inaccurate ground truth measurement at the edge of the inert item instead of its center of mass.

7.2 DYNAMIC SURVEY COVERAGE

During MM dynamic surveys at Fort Ord, along-track separation distances met the 15 cm metric with the highest percentage of points over 15 cm being 0.8%. All sites had minor exceedances of the maximum along-track separation of 20 cm. Because the DGM was done with the aim of having an across-track spacing of 0.5 m, the areas with along-track separations exceeding 20 cm were still characterized adequately by the surrounding lines. Across-track separation distances met the 0.5 m metric with the lowest passing percentage being 99.20%. Minor exceedances were for the 1 m across-track maximum at sites 11A and 12B.

At RSA, >99% of the dynamic TEMTADS data had across-track separation within 0.5 m, and 100% were within 0.7 m. Fill-in surveys were required in order to meet this metric. More than 98.8% of data were within 15 cm when analyzing the along-track separation. However, the along-track objective was not met for all data collected, as the along-line data separation was within 20 cm for 99.9% of dynamic data.

7.3 DETECTION OF ALL TOI

At Fort Ord, 36 of the 40 blind seeds were selected for investigation and recovered. All recovered seeds were located within 0.5 m with the largest offset being 0.18 m and a median offset of 0.04 m. The four seeds not selected for investigation were detected outside of the four full clearance grids, but were not selected as part of the higher confidence TOIs during dynamic data classification performed by BTG.

At RSA, all items were detected during tests performed in dynamic mode at the IVS. Inversion of dynamic data was not a viable option with UX-Analyze at this time, so detection was based on amplitude responses over the IVS objects. Of 28 blind seeds, one was not selected as a target during the detection survey. This seed was located at 0.5 m depth, near the depth of detections for a medium ISO at RSA.

7.4 CUED DATA LOCATION

All dynamic versus cued location offsets in the low-density area (12A), and the high-density areas (11A and 11B) were <40 cm. At Site 12B (the medium-density area), one anomaly had dynamic-to-cued location offset >40 cm, and dig results showed duplicate targets for the same anomaly. For the 150 targets spread over Unit 11, the offsets between the initial EM61 target picks and the inverted anomaly locations were all <40 cm.

At RSA, all of the targets' modeled locations were within 0.4 m of the center of the TEMTADS, with the exception of 22 category 0 targets. Recollections were made in the field based on the NRL field inversion software, but recollections were not assigned based on UX-Analyze inversion results.

7.5 CORRECTLY CLASSIFY TOI

TOI Classification at Fort Ord

At Fort Ord, 38 blind seeds were selected as targets for validation. The location and type for two of these were disclosed to BTG for calibration purposes resulting in 36 blind seeds. Of these, 34 were classified as TOIs. A medium ISO buried at a depth of 18 cm, located in the high-density target area, had a poor tertiary polarizability, which resulted in a higher overall misfit. A review concluded that it should have been marked as training data based on primary and secondary polarizabilities. The other was a 40mm projectile buried at a depth of 30 cm, located in what was considered a low-density target area; this target was likely too deep for reliable classification.

The objective for classifying 100% of large munitions items was not met in the high-density area due to the incorrect classification of one 155mm projectile in the TOI 1 dig list resulting in 97% of the large munitions being correctly classified. During dig operations, 30 TOI 1 items, including 22 155mm projectiles, 3 155mm inert seeds, and 6 large ISOs, were recovered. One 155mm projectile was selected as training data. One 155mm projectile at a depth of 42 cm was incorrectly classified as clutter in the TOI 1 dig list. The best match to target 50048 was a Stokes mortar; however, this item was classified as TOI 2 and included as a dig in the TOI 1 and TOI 2 combined dig list.

The objective for classifying 75% of smaller munitions items was met in the low-, medium-, and high-density areas. In general, the classification results for smaller munitions were better in the low-density area. A breakdown by item type can be found in the site demonstration report. All of the TOI 2 155mm projectiles with depths ranging from 69 to 97 cm were classified as TOI 1, which was unexpected based on test results obtained in the training pit where measurements of deeper 155mm projectiles produced poor inversion results.

TOI Classification at Redstone Arsenal

Of 28 blind seeds, 20 were correctly identified as TOIs, 4 as training digs, and 4 classified as "can't decide." The four seeds classified as "can't decide" were still above the stop-dig threshold but were not classified as high confidence TOI; the UX-Analyze decision metric for their respective targets was below the decision metric threshold that was used as the cut-off point for high confidence TOI.

An additional 26 digs resulted in TOIs with 19 properly predicted as TOIs. Of these, 19 were classified as high confidence TOI and the remaining 7 were classified as "can't decide." All non-seed-related TOIs recovered during the intrusive investigation of TEMTADS targets were portions of M50-X incendiary bomblets. Given the single pass of library validation and digging performed, the polarizability library entries did not change based on incoming dig results, and M50-X bomblets or their subsections were not included in the library.

An overlying goal of this project was the detection and classification of large munitions, such as 4.2-in mortars at a depth of approximately 90 cm. While no preexisting TOI of this size were discovered during the intrusive investigations at Site RSA-073, six blind seeds of comparable size were detected and cued during the demonstration. Emplacement depths of these seeds ranged from 45 cm to 80 cm bgs. The two deepest of these seeds had decision metrics below 0.925 threshold used for high confidence TOIs. A 0.923 decision statistic was obtained for a 105mm mortar at 70 cm and a 0.857 decision statistic was obtained for a 4.2-in mortar at 80 cm. A large ISO, whose depth of emplacement was also 60 cm, had a decision metric of 0.972. Based on these few examples, depths much more than 2 ft seem to present a challenge for the TEMTADS, when using standard processing procedures within the noise present at this site.

7.6 CORRECTLY CLASSIFY NON-TOI

Classification of Non-TOI at Fort Ord

The objective was met in the stage 1 dig list with the best performance in the low-density area. This result was anticipated since targets resulting from larger items were expected to be a small portion of the actual targets on site.

For the stage 2 dig list, the objective was met for the low-density area but not for the medium- and high-density area. This result was also expected. One issue was the similar physical dimensions between frag and smaller munitions such as 40mm projectiles, which resulted in library matches within the range of those observed in training data. In addition, training data requests revealed smaller munitions such as 40mm projectiles with relatively poor library match results and higher misfit values. Because of this, the dig list was expanded to include targets with larger misfit values.

Classification of Non-TOI at Redstone Arsenal

This objective was met. Of the 164 non-TOIs items investigated intrusively, 70.12% of non-TOIs were correctly identified as non-TOIs. This number would improve significantly after the removal of fuze components from the polarization library, which accounted for 37% of the non-TOI items that were identified as TOIs or potential TOIs. There was only one instance were a match to a fuze component corresponded to a dig of munitions potentially presenting an explosive hazard and therefore considered a TOI, but not of typical UXO shape.

7.7 MINIMIZE “CAN’T ANALYZE” ANOMALIES

The objective of <5% of anomalies being categorized as “can’t analyze” was achieved at both project sites. Only two targets were categorized as “can’t analyze” for a total of 0.07% at Fort Ord. At RSA, this objective was met with 3.06% of cued data measurements having modeled polarizabilities that resulted in “can’t analyze” categorization.

7.8 CORRECTLY PLACE THE “STOP DIG” THRESHOLD

At Fort Ord, the TOI 1 dig list included a total of 219 digs out of 2,803 targets, including training targets and “can’t analyze” targets. This resulted in approximately 8% of the available targets being selected for excavation, and one 155mm projectile being incorrectly categorized. Adjusting the stop-dig point to include this target would result in the addition of 165 digs resulting in 384 digs, which is about 14% of the available targets.

The combined TOI 1 and TOI 2 dig list included a total of 1,500 out of 2,803 targets, including training targets and “can’t analyze” targets. This resulted in 54% of the available targets being selected for excavation, with 16 TOIs still classified as clutter. For the low-, medium-, and high-density target areas combined, the stop-dig threshold selected for TOI 2 successfully identified well over 75% of smaller TOIs. However, the combined list contains a large number of non-TOIs categorized as TOIs.

At RSA, this objective was met with one caveat: a section of an M50-X was below the stop-dig threshold. However, this target was shared with another measurement that placed it above the stop-dig point. Additionally, this target had polarizabilities that were not modeled conclusively by UX-Analyze resulting in no library match for the best multi-item polarizabilities. Even though a decision metric was assigned that placed it in category 3, the target should have been assigned to category 0. The difficulty with the M50 is the hex portion can be any size or shape when not intact and still be considered a UXO or MEC. Note that a receiver-operating characteristic curve was not created for this demonstration due to the limited number of intrusive investigations relative to the total target list.

7.9 CORRECT ANOMALY LOCATIONS

Correct Anomaly Location at Fort Ord

In the low-density area, one target was offset 44 cm from the final predicted location to the actual dig location, resulting in >99% of the targets being within 40 cm, meeting the objective. Of the 403 anomaly locations, 69 (17%) show depth offsets >10 cm.

In the medium-density area, 16 targets had offsets >40 cm from the predicted locations to the actual dig locations, resulting in 97% of the predicted locations being within 40 cm, meeting the objective. Out of 495 locations, 113 (23%) had depth offsets >10 cm. Of these, 17 failures were associated with excavation locations where multiple items were recovered.

In the high-density area at Site 11A, 12 targets were >40 cm between the predicted locations and the dig locations resulting in 98% of the targets being within 40 cm, meeting the objective.

Between cued and dig locations, 38% of depth offsets were >10 cm. For Site 11B, 19 targets had offsets of >40 cm between the predicted locations and the dig locations, resulting in 98% of the targets being within the metric, meeting the objective. Almost half of the depth offsets for 11B were >10 cm. For the 150 additional targets in Unit 11, five had offsets of >40 cm, leaving 97% of the targets being within 40 cm, meeting the objective. Depth comparison between inversion and dig list results shows 50 out of 150 locations with depth offsets >10 cm.

Correct Anomaly Location at RSA

The horizontal offset objective was not met, as 89.524% of measured horizontal dig locations were within 25 cm of the predicted location. The objective regarding depth offsets was not met as 79.82% of measured dig depths were within 10 cm predicted depth. More than 96% of the predicted depths were within 25 cm of ground truth.

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8.0 COST ASSESSMENT

The cost assessment includes costs tracked for this project. This section presents cost and production data and analysis for the MM demonstration at Fort Ord and the TEMTADS demonstration at RSA.

8.1 COST SUMMARY

Costs for each project task are shown in **Table 8-1** and **Table 8-2** below. Travel and equipment costs are distributed by task. Unit costs for activities such as dynamic or cued surveys are not provided because they are distorted by costs absorbed by the Installation and by significant investments in training multiple CB&I geophysicists.

Table 8-1. Project Cost Breakdown by Task, Fort Ord

Budget element	Cost by Task	% of Total
Project set up and work plan	17,897	3%
Metal mapper repair	12,975	2%
UXO setup (brush cutting)	27,118	4%
DGM setup (IVS and equipment)	21,307	3%
Setup	32,627	5%
Dynamic surveys	23,890	4%
Cued surveys	69,569	11%
Reacquisitions	18,271	3%
DGM home office	158,560	25%
Subsurface investigations (incl geo)	141,786	22%
Report	69,641	12%
Project management	42,686	7%
	636,327	

Table 8-2. Cost Breakdown by Task, RSA

Budget element	Cost by Task	% of Total
Project set up and work plan	19,820	4%
Site and Equipment Prep	7,966	
Dynamic surveys	160,816	31%
Cued surveys	53,914	11%
DGM home office	211,985	42%
Subsurface investigations (incl geo)	308	0%
Report	19,304	5%
Project management	32,551	6%
	506,664	

8.2 COST DRIVERS

The costs were primarily controlled by production rates, data processing, and QC costs. At Fort Ord, the average daily production rate for dynamic surveys was 0.8 acres while the average production rate at RSA was 0.22 acres. The two largest factors that influenced the lower production rates at RSA included the dense tree cover and weather delays. The average daily production rate for cued surveys at Fort Ord was 200 targets while the average daily production for RSA was 80 targets. The production rate for cued surveys at RSA was mostly influenced by the necessity to use an RTS for locating targets that required multiple set-ups and break-downs due to the dense tree cover. Processing and QC costs included training operations for CB&I personal, which affected the final totals. Based on experience at Fort Ord and RSA, almost twice the time spent in the field is needed for processing. Likewise, the time spent on QC operations should also be at least equal to the time spent in the field (a full day of QC for each day of field work). In both projects, equipment including tow vehicles and positioning systems were provided and were not tracked. Although not available when the Fort Ord and RSA projects were completed, the rental rate for the newest generation MM is $750/day, which would also add a significant cost for a project using AC.

8.3 COST BENEFIT

The following cost analysis is based on the results obtained at Fort Ord where AC was applied to large munitions. Assuming a 100-acre site with an average target count of 300 targets per acre and a 78% reduction in the number of excavations, the following estimates were made.

- EM61 survey and 100% target investigation – $2.5M ($25,000/acre)
- AC Survey and cued target investigation with a 78% reduction in the number of targets requiring investigation – $1.5M
- Combined EM61 survey with AC cued survey – $1.0M

In both cases, AC provides significant savings over the EM61 survey.

When trying to classify smaller items in the more cluttered areas encountered at Fort Ord, a large number of non-TOI targets were also excavated. A reduction of only 46% of available targets was achieved leaving 54% targets requiring excavation. Based on budget analysis, the comparison between conventional EM61 surveys and both dynamic and cued AC surveys showed no real cost benefit. However, when combining conventional EM61 surveys with cued AC surveys, the savings are significant.

9.0 IMPLEMENTATION ISSUES

The most significant implementation issues during data collection at Fort Ord and RSA were associated with the initial condition of the MM and TEMTADS units when received by CB&I. The issues were likely due to the age of both sensor systems during 2014 and 2015 when field work was undertaken. The MM unit required multiple repairs for transmitter boards and wiring.

The initial TEMTADS unit from NRL was determined to be malfunctioning, and the electronics unit was swapped with a unit recently demobilized by another contractor. During field work at RSA, rain was common, and instructions from NRL staff were to avoid any rain, which created significant delays in initial testing and data collection.

At RSA, importing TEMTADS data with RTS-based positioning into Oasis montaj proved a challenge during initial testing. A custom executable (GX) was written to provide correct positioning information for the .gps files recorded by the TEMTADS unit in cued mode, requiring extra steps during preprocessing. However, by the time data processing was undertaken, resource files, provided by Acorn, were applied to Oasis montaj 8.5.2 allowing for the direct import of cued data with RTS positioning.

The intention was to generate source models from dynamic data as well as cued data from both sites. However, at the time of the RSA demonstration, dynamic processing capabilities of UX-Analyze were still not fully mature. Dynamic TEMTADS data could be loaded into a beta version of Oasis montaj 9.0 or with customized resource files from Acorn and Oasis montaj 8.5.2, but not through the then current version 8.5.5. More importantly, the ability to perform inversions with dynamic data was not present.

At Fort Ord and RSA, complications with data processing software related to the maturity of the software, and the experience level of CB&I analysts with the software, meant that portions of the data were being processed and reviewed after data collection was complete. Corrective measures based on QC metrics were not possible to administer immediately as a result.

Heavy machinery was a necessity for moving the MM at Fort Ord. As such, the skill of the operator with such machinery was key to the speed of data collection and the proper positioning of the sensor over targets. Geophysicists without experience operating a skid steer were able to achieve production rates ranging from 20–25 cued targets per hour. A skilled equipment operator, well versed in geophysical data collection, was able to achieve rates between 40 and 50 cued targets per hour.

At RSA, where RTS positioning was necessary, it was determined that the Trimble S7 provided a more consistent data stream at the desired sample rates than a Leica TPS system, which was initially selected.

The variability of signatures for M50 segments of various sizes at RSA meant library matches to these items could be difficult to obtain, and adding all potential pieces to the library was not practical.

Some of the smallest segments were still considered to be potentially hazardous, and if included as TOI, reducing the numbers of non-TOI digs would be more difficult as the segments would match frag and small debris. At a site where M50s were present, the practicality of using AC would need to be evaluated during project planning (if the M50 was considered a TOI) to better define limits of the work. The project team would need to decide if the M50 is considered a TOI and whether an alternative strategy specific to the M50 was necessary.

10.0 REFERENCES

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